Int J Life Cycle Assess (2012) 17:997–1014
DOI 10.1007/s11367-012-0440-9

LCA IN TRANSPORTATION

Environmental impacts of hybrid and electric vehicles—a review

Troy R. Hawkins · Ola Moa Gausen · Anders Hammer Strømman

Received: 14 September 2010 / Accepted: 7 May 2012 / Published online: 31 May 2012

Abstract

Purpose A literature review is undertaken to understand how well existing studies of the environmental impacts of hybrid and electric vehicles (EV) address the full life cycle of these technologies. Results of studies are synthesized to compare the global warming potential (GWP) of different EV and internal combustion engine vehicle (ICEV) options. Other impacts are compared; however, data availability limits the extent to which this could be accomplished.

Method We define what should be included in a complete, state-of-the-art environmental assessment of hybrid and electric vehicles considering components and life cycle stages, emission categories, impact categories, and resource use and compare the content of 51 environmental assessments of hybrid and electric vehicles to our definition. Impact assessment results associated with full life cycle inventories (LCI) are compared for GWP as well as emissions of other pollutants. GWP results by life cycle stage and key parameters are extracted and used to perform a meta-analysis quantifying the impacts of vehicle options.

Results Few studies provide a full LCI for EVs together with assessment of multiple impacts. Research has focused on well to wheel studies comparing fossil fuel and electricity use as the use phase has been seen to dominate the life cycle of vehicles. Only very recently have studies begun to better address production impacts. Apart from batteries, very few studies provide transparent LCIs of other key EV drivetrain components. Estimates of EV energy use in the literature span a wide range, 0.10–0.24 kWh/km. Similarly, battery and vehicle lifetime plays an important role in results, yet lifetime assumptions range between 150,000–300,000 km. CO_2 and GWP are the most frequently reported results. Compiled results suggest the GWP of EVs powered by coal electricity falls between small and large conventional vehicles while EVs powered by natural gas or low-carbon energy sources perform better than the most efficient ICEVs. EV results in regions dependant on coal electricity demonstrated a trend toward increased SO_x emissions compared to fuel use by ICEVs.

Conclusions Moving forward research should focus on providing consensus around a transparent inventory for production of electric vehicles, appropriate electricity grid mix assumptions, the implications of EV adoption on the existing grid, and means of comparing vehicle on the basis of common driving and charging patterns. Although EVs appear to demonstrate decreases in GWP compared to conventional ICEVs, high efficiency ICEVs and grid-independent hybrid electric vehicles perform better than EVs using coal-fired electricity.

Keywords Batteries · Electric vehicles · Greenhouse gas · Plug-in hybrid · Transportation

Responsible editor: Hans-Jörg Althaus

Electronic supplementary material The online version of this article (doi:10.1007/s11367-012-0440-9) contains supplementary material, which is available to authorized users.

T. R. Hawkins (✉) · O. M. Gausen · A. H. Strømman
Industrial Ecology Program/Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU),
Trondheim, Norway
e-mail: trh@alumni.cmu.edu

1 Introduction

Many governments and advocacy groups promote adoption of hybrid and electric vehicles (EV) as an important part of the portfolio of technologies required for reducing GHG emissions and energy use (Greenpeace 2008; Kendall

2008; Commission on Oil Independence 2006; Bellona 2009; Spongenber 2008; WBCSD 2004). Recent interest in climate policy has resulted in many of the biggest automobile producers increasing production of mild hybrid vehicles such as the Honda Civic and Insight Hybrids, Chevrolet Malibu Hybrid, and the Mercedes-Benz S400 Hybrid; full hybrids such as the Toyota Prius and Ford Fusion Hybrid; plug-in hybrids such as the Chevrolet Volt, Renault Kangoo PHEV, and battery electric vehicles currently produced or near production including the Mitsubishi i-MiEV, Nissan Leaf, Renault Kangoo BEV, Ford Electric Focus, Think, and Tesla Roadster.

Interest in EVs stems from their offer of low or no tailpipe emissions. However, as Lave and Hendrickson argued in response to California's proposed zero emissions vehicles policy in the mid 1990s, the direct tailpipe emissions are only one aspect of the environmental impacts of EVs (Lave et al. 1995a). To ensure that the promotion of EVs to reduce greenhouse gas (GHG) emissions from transport does not lead to other undesired consequences, it is critical to conduct rigorous, scenario-based environmental assessments of proposed technologies before their widespread adoption. Life cycle assessment (LCA) is the tool of choice for comparing the environmental impacts of transportation options because it explicitly quantifies resource use and environmental releases along the entire life cycle of a product. Here we distinguish three types of vehicles, battery electric vehicles (BEV) which use only an electric motor, internal combustion engine vehicles (ICEV) which use only an internal combustion engine (ICE), and hybrid electric vehicles (HEV) which use both an electric motor (EM) and ICE. We use HEV as a general term including both plug-in hybrid electric vehicles (PHEV) which can be charged either from the electricity grid and a grid-independent HEV (GI-HEV) which is only be charged by the ICE. We use the term electric vehicle (EV) to refer collectively to BEVs and HEVs. In the comparison of technologies, it is also important to distinguish between charge sustaining and charge depleting modes for PHEVs. Charge sustaining refers to operation under ICE power which does not require battery assistance while charge depleting refers to operation under battery power. For PHEVs, it is also important to note that vehicles differ in distance they can travel under solely battery power, referred to as all electric range (AER). These differences relate to battery requirements and mass and thus also affect energy use in operation. A table listing acronyms used in this article as well as further discussion of these technologies is provided in the Supporting Information (SI).

In the 1990s, several studies were performed focusing on the air quality and the environmental impacts and benefits of EVs (Kazimi 1997; Vimmerstedt et al. 1996; Vimmerstedt et al. 1995; Wang and Santini 1993; Wang et al. 1990; Lave et al. 1995a). These studies provided comparative tail-pipe emissions, and highlighted concerns about additional emissions associated with increased battery production (Lave et al. 1995a). Related, early LCA studies pointed out the risk of considering isolated mechanisms and impacts within a larger system (Lave et al. 1995a).

More complete LCA studies of EVs and car batteries were undertaken by U.S. national laboratories in the late 1990s (Wang et al. 1997; Singh et al. 1998) which led to the development of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) 1-series model for estimating vehicle emissions, fuel-use, and energy use in a well-to-wheel (WTW) perspective (Wang et al. 1997). Later a similar GREET 2-series vehicle production model was developed (Burnham et al. 2006). GREET has been used for a number of studies and continues to be updated (Baptista et al. 2009; Daniel and Rosen 2002; General Motors Corporation 2001; Kitner-Meyer et al. 2007; Samaras and Meisterling 2008; Santini and Vyas 2008; Wang et al. 1997). Other tools developed during this period and applied to study the use phase of different vehicle technologies are the Advanced Vehicle Simulator (ADVISOR) model first released publicly in 1998 and since commercialized and the Powertrain System Analysis Toolkit (PSAT). This tool simulates vehicle fuel consumption and emissions under different driving patterns such as the New European Driving Cycle (DieselNet 2000) or the U.S. EPA Federal Test Procedure.

Understanding the system-wide environmental impacts of replacing ICEVs with an alternate technology such as EVs involves a wide range of considerations (Hacker et al. 2009). Moving forward, it is important to codify what is known about the environmental impacts of EVs and to identify the most important gaps in our knowledge which should be filled to create effective policy for mitigating the environmental impacts of personal transportation. Here we describe the state of the art in environmental analysis of light-duty EVs in order to identify parts of the life cycle, emissions, and environmental impacts which have not received sufficient attention and then compare studies based on individual life cycle stages and key parameters.

2 State-of-the-art LCA for electric vehicles

Ideally, a full LCA of an EV should assess all direct and indirect or upstream processes relating to its production, use, and end of life. Within the ISO 14040 and 14044 guidelines for life cycle inventory (LCI) data requirements are addressed within the study's goal and scope definition (ISO 2006a, b). Generally a system boundary is set within which process data are collected to meet the goal of the study and in practice, usually a set of processes assumed to

contribute negligibly to the end result are excluded. These boundary cut-off problems are reduced in studies which use a generalized background dataset such as EcoInvent (Swiss Center for LCI 2009) GaBi or an environmentally extended input–output dataset (Tukker et al. 2008; Lave et al. 1995b; Joshi 2000; Suh et al. 2004; Hawkins et al. 2007) to model those processes for which study specific data are not collected. Because of the complex interaction between EVs and the larger system including infrastructure, other vehicle technologies, other fuels and their distribution systems, and collective transportation options, it can be difficult to know a priori which processes can be excluded. Here we present what we believe to be a complete, albeit stylized, life cycle for EVs, and system-context appropriate for comparison with ICEVs. For simplicity's sake, we exclude some more complex aspects such as interactions with certain infrastructure components and other vehicle technologies.

Figure 1 shows a simplified flow chart of an LCA for EVs. The LCA can be broken into four major components: production of the vehicle itself; the use phase; production and distribution of the use phase energy consisting of transmission, and distribution of electricity and the production and distribution of other fuels in the case of HEVs; and end of life. Vehicle production, depicted in the central box in Fig. 1, can be further subdivided into the components which comprise the vehicle. While ideally all sub-components could be distinguished in an LCI, in practice this is very difficult. The choice of sub-components included in Fig. 1 is based on those most relevant to the evaluation of EVs.

In LCI of new vehicle technologies such as biofuel vehicles or EVs, it is sufficient to assume that many components of the vehicle do not differ significantly from those of fossil fuel vehicles (Buchert 2010; Samaras and Meisterling 2008; Notter et al. 2010). In the case of BEVs several adjustments are made, fuel tanks are replaced with batteries and temperature control systems, fuel lines are replaced with wires, the ICE is replaced with an electric motor, electronic combustion control systems are replaced with electrical system controls, and a regenerative braking system may be added to the conventional one. In some cases, the additional battery mass requires changes to the vehicle structure itself. We have explicitly listed the production of electronics as it is likely EVs require additional electronics when compared with ICEVs. Tires are also included explicitly as additional battery mass can have an effect on tire specifications, resistance, and wear. Raw material extraction, processing, and manufacturing are represented to the left with the understanding that these stages apply for all vehicle components. In addition there are sub-processes such as transportation of materials throughout supply chains, production of

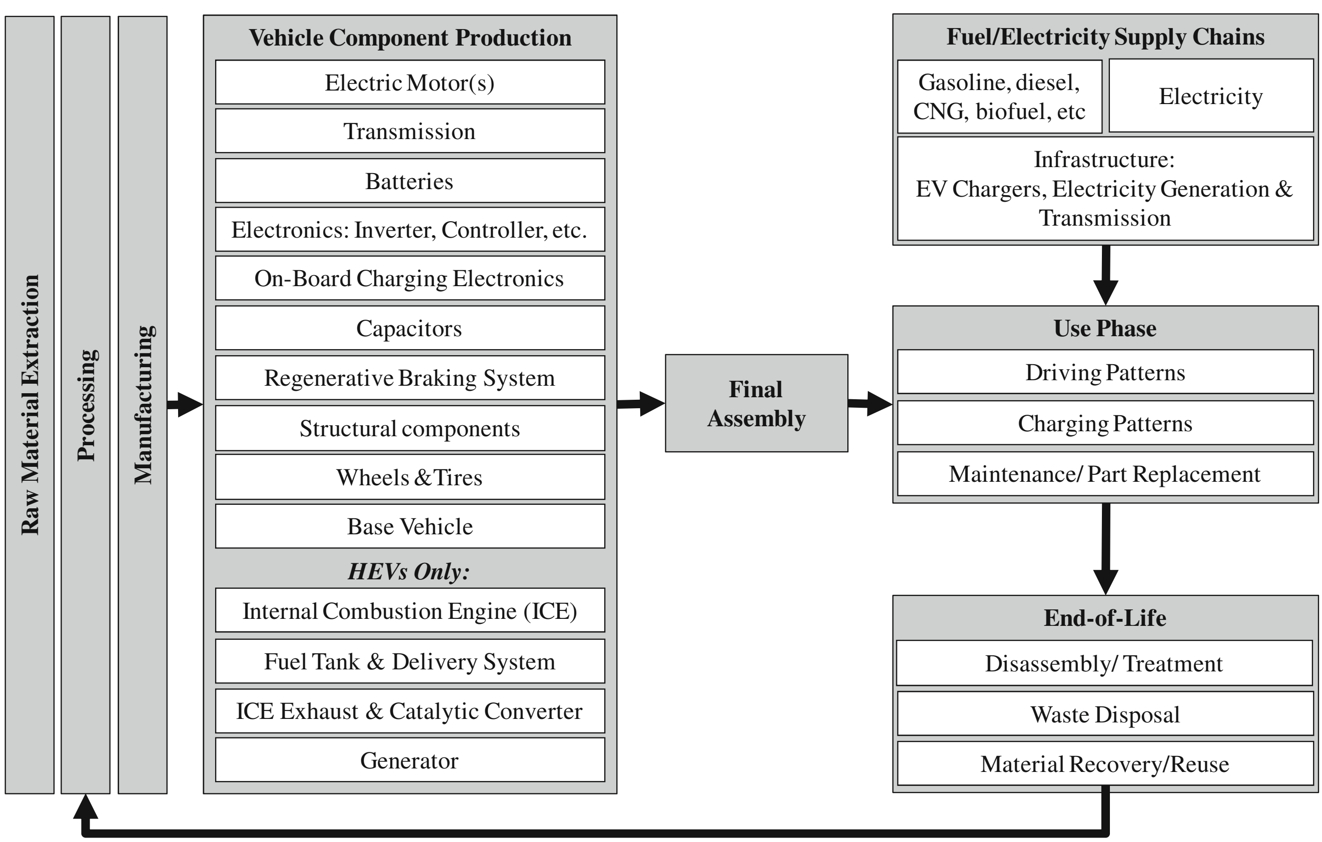

Fig. 1 Simplified flow chart of the life cycle of a hybrid or electric vehicle

processing facilities, electricity, etc., which have been omitted from the figure for simplicity's sake.

In assessing the vehicles use phase driving patterns must be considered to determine electricity and fuel use. The frequency and depth of battery cycles are important as they determine the lifetime and efficiency of the battery. The energy requirements of the vehicle also depend heavily on its load, in terms of passengers or goods, and acceleration patterns. Acceleration subjects batteries to high power draw. Vehicles designed for more and higher acceleration require larger amounts of batteries to supply the high power and energy demands. Maintenance of the vehicle must also be included in the use phase. If a detailed LCI of the vehicle exists, the production of replacement parts can be considered the same as production of the originals in terms of environmental impact. Feeding into the use phase is electricity and in the case of HEVs also fossil- or bio-fuel. The LCI should include the material extraction, processing, transport, distribution, and infrastructure associated with these energy sources.

Vehicle end of life plays an important role in the result of the LCA of EVs. Studies often assume that certain effects of producing materials can be offset by the recycling of those materials. However, it is important to understand the feasibility of recycling materials and the degradation of materials. Not all materials in batteries, for example, can be reused in batteries given current material prices. In many cases, materials are down-cycled into other applications for which the environmental impacts of producing materials are significantly less than those for the EV system.

When considering the adoption of EVs, it is important to consider the system into which they will fit. At scale EVs may require additional electricity generation or transmission capacity. The timing of charging can affect peak electricity use and the grid mix effectively used by EVs. The feasibility of battery recycling or charging schemes will depend on fleet size.

3 Evaluation of existing studies

3.1 Scope and completeness

We benchmarked 55 studies from peer-reviewed and gray literature containing environmental, energy or material assessments of EVs or key components of EVs against the state-of-the-art LCA of EVs presented in the previous section (Fig. 2). A detailed explanation of the choices made in benchmarking can be found in the SI. Of the 55 studies, 42 contain environmental or energy assessments of either vehicles or vehicle operation. The others contain some information useful for environmental assessment of EV technologies but were performed to address a more specific goal and therefore have a different scope. 31 studies assess GI-HEVs (Bandivadekar 2008; Boureima et al. 2009; Bravo et al. 2006; Brinkman et al. 2005; Burnham et al. 2006; Daniel and Rosen 2002; Dhingra et al. 2000; Eberhard and Tarpenning 2006; EPRI 2002, 2007; Fontaras et al. 2008; General Motors Corporation 2001; Hackney and de Neufville 2001; Hermance and Sasaki 1998; Jaramillo et al. 2009; Kalhammer et al. 2007; Lave and MacLean 2002; Mohamadabadi et al. 2009; Plotkin et al. 2002; Samaras and Meisterling 2008; Santini and Vyas 2008; Schexnayder et al. 2001; Stephan and Sullivan 2008; Van Mierlo et al. 2004; Wang et al. 1997; Williamson and Emadi 2005; Burke and Abeles 2004; Huo et al. 2010; Shiau et al. 2010; Mercedes-Benz 2009; King and Webber 2008), 23 assess PHEVs (Bandivadekar 2008; Baptista et al. 2009; Daniel and Rosen 2002; Elgowainy et al. 2009; EPRI 2002, 2007; Gage 2003; Jaramillo et al. 2009; Kalhammer et al. 2007; Karbowski et al. 2007; Kitner-Meyer et al. 2007; Letendre et al. 2008; Parks et al. 2007; Plotkin et al. 2002; Samaras and Meisterling 2008; Santini and Vyas 2008; Shiau et al. 2008; Sioshansi and Denholm 2009; Wang et al. 1997; Gaines et al. 2007; Gaines and Nelson 2010; Huo et al. 2010; Shiau et al. 2010; King and Webber 2008), and 14 assess BEVs (Baptista et al. 2009; Bauen and Hart 2000; Boureima et al. 2009; Campanari et al. 2009; Daniel and Rosen 2002; Eberhard and Tarpenning 2006; Hackney and de Neufville 2001; Jacobson 2009; Kalhammer et al. 2007; Kendall 2008; McCleese and LaPuma 2002; Van Mierlo et al. 2004; Notter et al. 2010; King and Webber 2008). Most papers compare results with emissions or energy use of ICEVs.

Ten studies containing a LCI for an EV include battery production (Schexnayder et al. 2001; McCleese and LaPuma 2002; Bandivadekar 2008; Boureima et al. 2009; Jaramillo et al. 2009; Samaras and Meisterling 2008; Burnham et al. 2006; Shiau et al. 2008; Notter et al. 2010). Notter et al. (Notter et al. 2010) and Mercedes (Mercedes-Benz 2009) base their results on detailed inventories, but only Notter et al. provide inventory details. Majeau-Bettez et al. (2011) and Zackrisson et al. (2010) provide inventories for traction batteries, but not the entire vehicle. Other studies rely on the dataset contained in the GREET 2.7 model or their own estmates. Rydh and Sanden provide commonly cited values for battery manufacturing energy use (Rydh and Sanden 2005). Older studies usually assess NiMH, NiCd, or PbA batteries, while more recent studies generally address Li-ion. The GREET 2.7 model (Baptista et al. 2009; Burnham et al. 2006; Wang et al. 1997) includes vehicle electronics in the LCI of vehicle production but only in terms of plastic and copper material use, not other precious metals or silicon production (Burnham 2009). Because of the importance of batteries and electronics to the impact of EVs and because the LCI literature for

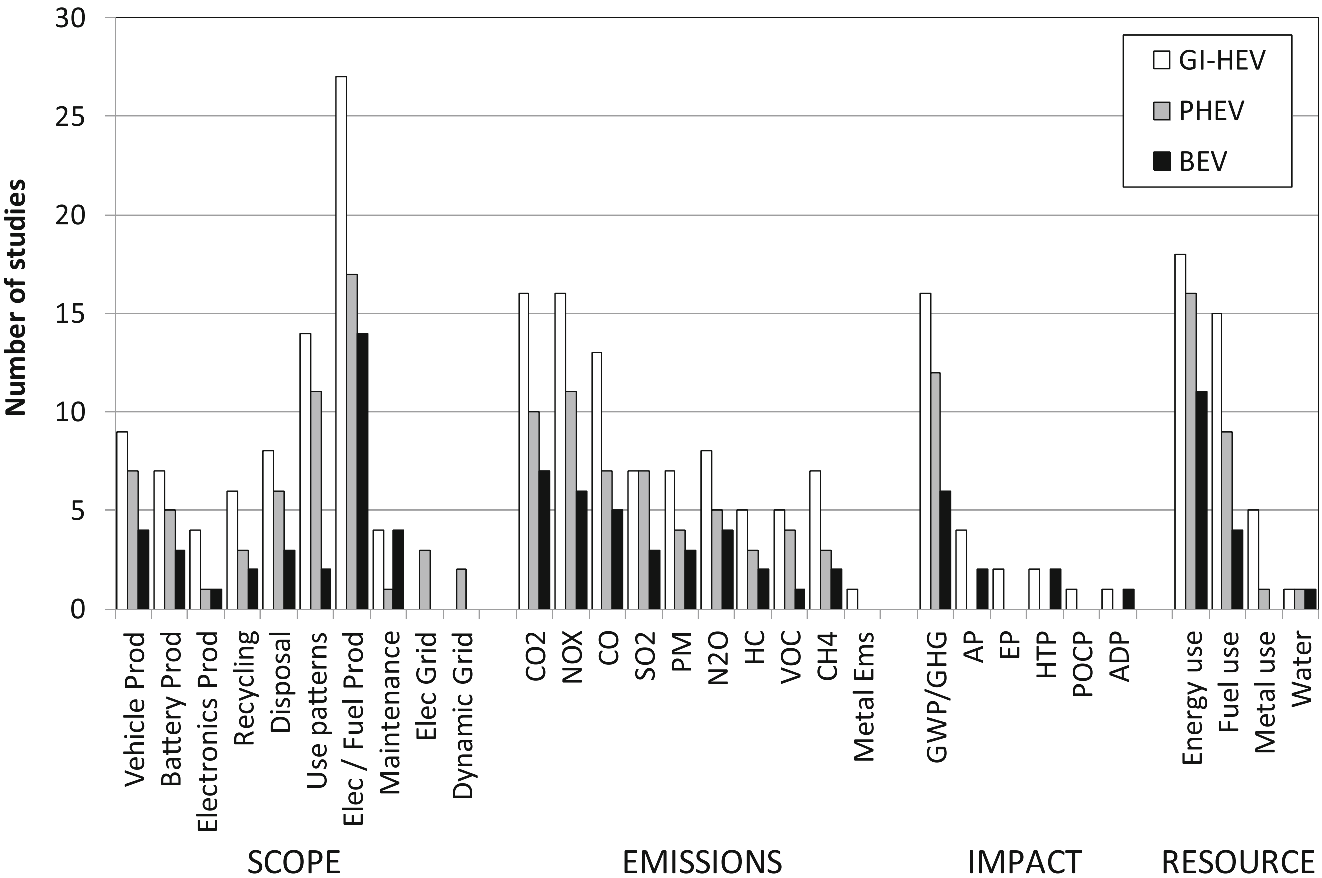

Fig. 2 Inclusiveness of existing studies of the environmental impacts of electric vehicles. Number of studies including different scopes, emissions, impact categories, and resource use. In total, 51 papers were considered

batteries was rather thin, we added 7 studies to our review which do not provide full assessments of EVs but which could be used to fill gaps in existing LCIs for batteries (Van den Bossche et al. 2006; Rydh 1999; 2001; 2003; Rydh and Karlstrom 2002; Rydh and Sanden 2005; Rantik 1999; Rydh and Svard 2003) and we added three sources providing information regarding electronic items (Toyota 2009; Tesla 2009; Spinella 2007).

Many of the papers we identified dealt with a narrow scope and did not include full LCI of the system we have defined. We identified 31 papers which include an LCI of liquid fuels and 23 including an LCI of electricity. Seven studies include an LCI for GI-HEVs, 5 for PHEVs, and only 4 for BEVs. Only 3 of the PHEV LCI studies (Shiau et al. 2008; Jaramillo et al. 2009; Samaras and Meisterling 2008; Shiau et al. 2009) and 3 BEV studies (Boureima et al. 2009; McCleese and LaPuma 2002; Notter et al. 2010) include explicit treatment of the battery life cycle, although it should be noted that the 3 PHEV studies all originate from the same research group and represent a single, yet evolving understanding of the PHEV battery LCI. The remaining studies base their inventories on these studies. End of life is only treated by a limited number of studies.

Maintenance is treated in 5 GI-HEV studies, 1 PHEV study, and 4 BEV studies. Generally the treatment of maintenance and parts replacement is rather rough considering the potential importance of battery replacement or increased maintenance associated with the complex control systems and regenerative braking systems found in HEVs. Nemry et al. (2008) and McCleese and LaPuma (2002) present explicit results for maintenance. Notter et al. and Röder also provide explicit inventories for the maintenance phase of EVs but maintenance results are aggregated with the use phase. Most studies we reviewed considered vehicle and battery lifetimes to be the same; however, Notter et al. (2010) consider a scenario where batteries are replaced within the lifetime of the vehicle. GREET 2.7 includes a rough estimation of the LCI associated with vehicle maintenance based on the LCI of expected replacement parts (Burnham et al. 2006). GREET 2.7 does not include the impacts of service stations themselves which include energy use and fugitive emissions (Lave et al. 1990), but refueling fugitive emissions are well-described by the US EPA (2011) Motor Vehicle Emission Simulator (MOVES) model.

Specific use patterns or driving cycles are described in 12 GI-HEV, 9 PHEV, and 3 BEV studies. Two papers consider

multiple driving cycles to determine their affect on the total energy use and/or emissions (Wang et al. 1997; Williamson and Emadi 2005). Three studies assess the additional load on the grid and 2 assess the effects of smart grid systems. These 5 studies only consider PHEVs and most of them are specific to the US.

Overall we found that the literature was surprisingly sparse with respect to some of the most environmentally-relevant components of EVs, batteries, electric motor, and electronic control systems. Decent LCI of electricity and fuel production are included in most studies, however the affect of EVs on the overall electricity system is less understood. Improving understanding would require compiling LCIs for the additional electricity infrastructure associated with the adoption of EVs including any necessary additional generation capacity, transmission, distribution, or control systems as well as new smart grid components such as advanced charge management systems.

Papers were also benchmarked with respect to inclusion of emissions of CO_2, NO_x, N_2O, CO, PM, CH_4, VOC, and different types of metals. Not surprisingly, most studies report either CO_2 emissions and/or GWP, 26 for GI-HEVs, 17 for PHEVs, and 11 for BEVs. Only one study reporting GWP also provided an explicit breakdown of component emissions (Brinkman et al. 2005). After GHGs, NO_x emissions or precursors to smog were the second most reported emissions followed by CO. SO_2, PM, N_2O, HC, VOC, and CH_4 emissions are assessed less frequently than GHGs, NO_x, or CO, but all are reported in multiple studies for each technology with the exception of VOCs which are only reported in one BEV study. Metal emissions are only reported explicitly by Schexnayder et al.'s (2001) study of a GI-HEV and in some other cases are incorporated in characterized emissions (Notter et al. 2010). Few studies report common mid-point indicators such as acidification potential (AP), human toxicity potential (HTP), or eutrophication potential (EP) and none of those that do provide transparent inventories.

In terms of resource use, energy is best accounted for. Total energy use was reported by 15 GI-HEV, 13 PHEV, and 8 BEV studies. Fuel use was reported by 13 GI-HEV and 7 PHEV studies. Metal use is accounted for by four studies which address GI-HEVs, one of which also includes results for PHEVs (Wang et al. 1997). Concerns regarding the availability of key resources including rare earth metals (Nd, La, Ce, Pr) in NiMH batteries, cobalt in both NiMH and Li-ion batteries, and lithium in Li-ion batteries are addressed in a handful of studies (Gaines and Nelson 2010; Rydh and Svard 2003; Andersson and Råde 2001; Will 1996). These studies are discussed in the SI.

To determine the coverage of existing LCI studies relative to the items included in our ideal scope, emissions, impacts, and resource use, we calculated the percentages of each list addressed in studies of GI-HEVs, PHEVs, and BEVs. By technology, studies of GI-HEVs and PHEVs were most complete although in all cases most studies address a relatively low percentage of the total sub-categories identified within these broader groups. Daniel and Rosen (2002), Bauen and Hart (2000), Boureima et al. (2009), and Notter et al. (2010) are the most inclusive BEV studies but differences in the way in which results are characterized and aggregated makes comparison across studies difficult. Our observations indicate gaps in scopes, emissions, impacts, and resource use included in most papers. Such an observation does not infer poor quality, rather individual studies deal with only limited subsets of the full EV system. This result implies that care must be taken when interpreting results and that existing studies have provide results of only limited utility for informing policy decisions. It also highlights the need for more inclusive studies which consider a broad scope and a wide range of emissions to ensure that EV schemes intended to reduce GHG emissions do not cause unexpected problems.

3.2 Greenhouse gas emissions

Up to this point, we have provided an assessment of the completeness of the literature in describing the full suite of environmental impacts across the full life cycle and relevant component detail for EVs. In this section, we synthesize existing literature in order to provide a meta-analysis of current understanding of the environmental performance of different EVs and to determine the relative environmental impacts of EVs versus conventional ICEVs. To do this we compiled GHG emissions across studies and compared them with results of high quality LCAs of representative ICEVs. Because differences in scope and method made it difficult to compare totals, we perform the comparison separately for vehicle and battery production, electricity generation, fuel production, energy efficiency, and fuel combustion emissions. A similar comparison for indicators other than GWP was not possible as not enough studies provided such results. Details related to the life cycle impact of the fossil fuel supply chains, fuel consumption in ICEVs, and emissions related to fuel combustion are provided in the SI.

3.2.1 Combined results for vehicle and battery production

Because many studies do not provide enough detail to allow separation of impacts related to base vehicle production from those related to battery production, we begin by comparing combined results. In Section 3.2.2, we compare results from studies where battery production can be distinguished. Figure 3 compares the GWP of vehicle and battery production per kilometer. Results in 3a are adjusted for a

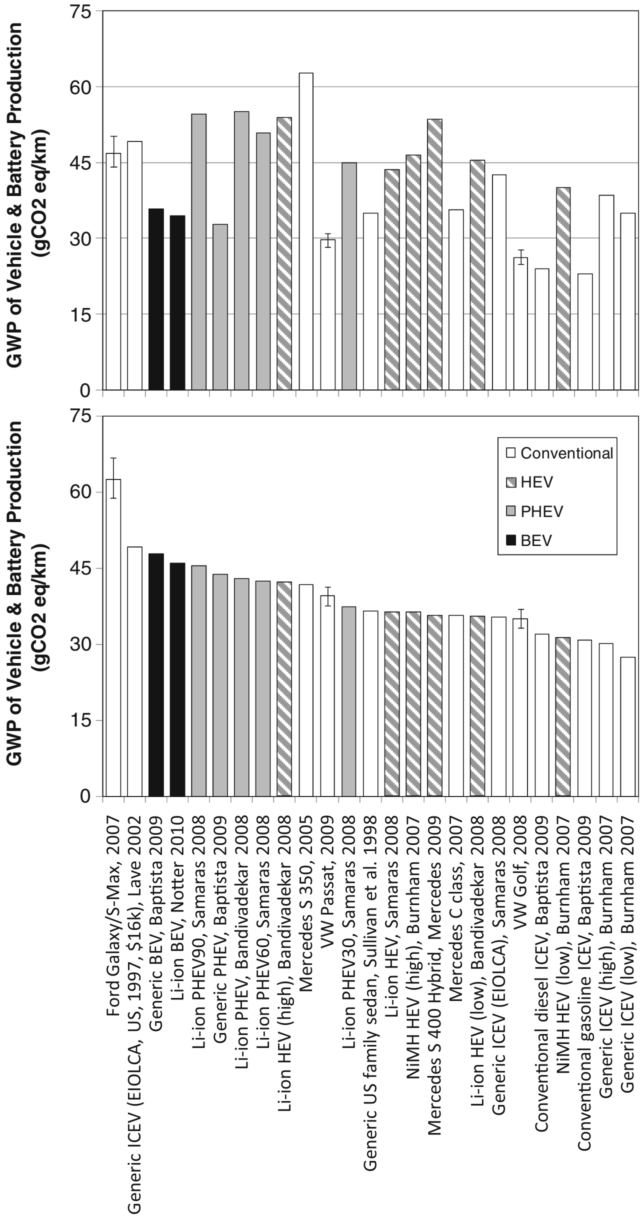

Fig. 3 Comparison of greenhouse gas emissions from vehicle and battery production. *Bottom figure* GWP or CO_2 emissions when GWP not presented, according to the lifetime assumptions of the original studies. *Top figure* GWP adjusted for a common lifetime of 200,000 km. *Whiskers* provide the range of GWP associated with different options available for that vehicle

common lifetime of 200,000 km, while 3b is based on the lifetime assumptions of the original studies. We chose a standard lifetime of 200,000 km because this is the average of the lifetimes in the studies reviewed and it represents the midpoint between the 3 most often assumed lifetimes of 150,000, 200,000, and 250,000 km. Clearly differences in designed life confound lifetime-harmonized results as demonstrated by the Mercedes S350 for which Mercedes assumes a 300,000-km lifetime. Table S5 in the Electronic Supplementary Material provides additional detail including the original lifetime assumptions. Clearly the lifetime has a significant effect on the GWP per km. However, it should be noted that the studies represented were published over a period of 10 years, during which time the expected lifetimes for Li-ion batteries have more than doubled (Zackrisson et al. 2010). Under the original lifetime assumptions, we also find ICEVs tend to have the lowest production-related GWP followed by GI-HEVs, then PHEVs, and finally BEVs reflecting the increased GWP associated with battery production. However, differences in the base vehicle also contribute to variation between studies. Variations from this trend for ICEVs seem to be related to vehicles with a larger mass than EVs which are generally smaller. In a separate comparison of ICEVs, we found that GWP from vehicle production scaled better with mass than with vehicle lifetime. However, for most of the EV studies, no mass data were available as these EV studies deal with hypothetical vehicles. This is important to consider when comparing EVs with ICEVs based on studies of differing scope and model considerations.

Although Fig. 3 provides a number of studies of EVs, care must be taken as often the underlying values are based on only a few and often roughly estimated data sources. For example, Baptista et al.'s (2009) results for PHEVs and BEVs are based on the GREET 2-series model (Burnham et al. 2006) adjusted to the European average electricity mix and Samaras and Meisterling's (2008) estimates are based on EIOLCA for vehicle production and a study of Li-ion batteries for photovoltaic systems (Rydh and Sanden 2005). Notter et al. (2010) provide the most complete LCI for a BEV.

Within individual studies of vehicle and battery production, the trend of increasing GWP associated with increasing degree of electrification (from ICEV to GI-HEV to PHEV to BEV) always holds. This reflects agreement across studies that the impact of battery production is significant within vehicle production and should be considered in comparisons across the full life cycle. However, differences in the definition of vehicles considered makes comparison across studies difficult. This makes using LCA to design policy regarding EVs challenging because conclusions about the relative benefits or detriments of EVs can only be drawn from studies of similar vehicles with common scope and boundary considerations.

3.2.2 Results specific to battery production

Where values were provided we also compared the GWP of battery production, see Fig. 4. Although kilometers are not the best functional unit for battery LCA (Matheys et al. 2007), we have compiled the GWP results in this way in order to be consistent with the functional unit most commonly used for EVs and because a number of studies do not

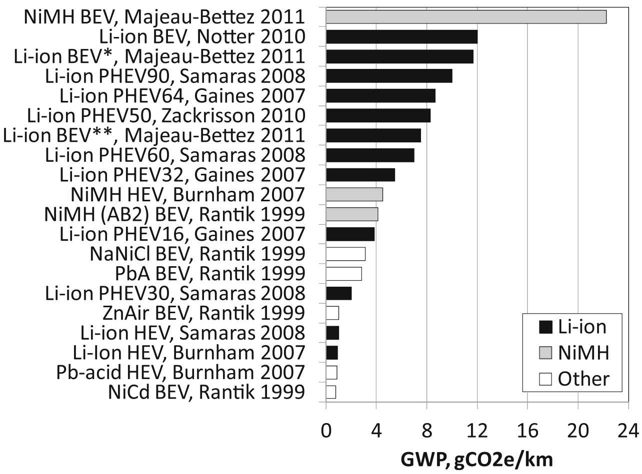

Fig. 4 Comparison of greenhouse gas emissions from battery production. Majeau-Bettez et al. (2011) values are obtained using the assumption of .53 MJ/km (Axsen et al. 2008). *Single asterisk* indicates positive electrode material $LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$. *Double asterisks* indicate positive electrode material $LiFePO_4$

provide the information required to do otherwise. It should also be noted up front that differences in Fig. 4 reflect differences in the battery mass associated with different vehicle types and the assumptions of individual studies. Majeau-Bettez et al. (2011), Notter et al. (2010), Zackrisson et al. (2010), and Rantik (1999) provide the most complete LCIs of traction batteries. Unfortunately Rantik's study has become somewhat dated as battery production technology has developed rapidly over the past 10 years. In addition Rantik does not include Li-ion batteries. The battery inventories used in GREET (Burnham et al. 2006) are still under development and are based on approximations of battery material contents making them uncertain and generally representative of a minimum bound. Gaines et al. (2007), from the group responsible for GREET, present different GWP results for Li-ion battery production than previously reported GREET 2 estimates, however few details are provided to describe how these values were obtained. Buchert (2010) presents material content and GWP for a Prius NiMH and related components under different recycling scenarios, but only a limited description of the method is available.

Samaras and Meisterling (2008) provide several values for Li-ion batteries associated with different all-electric ranges (AER) based on extrapolation of results from Rydh and Sanden's (2005) study of batteries in photovoltaic systems. Their emissions do not seem to scale directly with AER but rather to climb steeply from AER of 30 km to 60 km increasing by 250 % from 2 to 7 gCO_2e/km and then increasing only 42 % to 10 gCO_2e/km for AER of 90 km. In general battery production GWP for GI-HEVs and PHEVs is lower than BEVs due to their lower battery mass.

As EV technology has developed, understanding of battery manufacturing has improved as has capabilities for inventory development. The trend toward higher battery production GWP in more recent studies is related to fact that inventories have become more complete. Notter et al. provide a more recent LCI of lithium manganese oxide batteries and find production of the anode and cathode accounts for roughly half of the total GWP of the battery and production of the battery pack itself accounts for roughly 30 %. Majeau-Bettez et al. (2011) report the highest value, 22 gCO_2e/km for NiMH batteries while acknowledging that NiMH is not likely the technology of choice for future EVs. Notter et al. and Majeau-Bettez et al. provide the most complete inventories for full BEV batteries and obtain the highest Li-ion battery GWPs on a per kilometer basis owing both to the additional battery mass required for the longer AER of BEVs and their improved representation of supply chain processes. Note that the results of Majeau-Bettez et al. are significantly larger than those of Notter et al. when compared on a the basis of battery mass.

A key source of variability in battery production results within the context of EVs is battery lifetime. In battery literature, lifetime is generally measured in terms of charge–discharge cycles, however in the context of EVs a number of factors contribute to the realized lifetimes. No consensus regarding the lifetime of batteries exists with differences owing more to uncertainties in use patterns and consumer behavior than in charge–discharge cycles. For the Tesla Roadster Li-ion BEV, Tesla Motors estimates a battery lifetime of 5 years or 160,000 km (Tesla 2009), while Toyota estimates 240,000 km to be the lifetime of the NiMH battery used in its Prius (Toyota 2009), longer than the expected lifetime of the Prius itself. Lifetimes for different vehicles represented in the studies cited here range from 150,000 to 300,000 km, with one estimate placing the lifetime of a first-generation Prius at only 160,000 km based on observed annual driving patterns and the efficient time-governed lifetime considering maintenance costs (Spinella 2007). Two potential explanations for variability should be mentioned. First, expected lifetimes for batteries have increased significantly in recent years (Zackrisson et al. 2010), and second, lifetime varies significantly across technologies with lifetimes for 80 % depth of discharge ranging from roughly 3,000 charge–discharge cycles for NiMH or Li-ion with an nickel-cobalt-manganese-oxide cathode to 6,000 charge–discharge cycles for Li-ion with an iron-phosphate cathode as 80 % (Majeau-Bettez et al. 2011; Kalhammer et al. 2007; Shukla and Kumar 2008; Takahashi et al. 2005).

Majeau-Bettez et al. allocate impacts across the battery lifetime whereas Notter et al. and most other studies consider primarily the vehicle lifetime. Coincidentally, when Majeau-Bettez et al. results given as impacts per unit energy delivered to the drivetrain are scaled up based on energy use per kilometer, they match Notter et al. very closely. However, Majeau-Bettez et al. report a value 3.6 times higher for

a lithium-cobalt-nickel-manganese battery than Notter et al. report for a lithium-manganese-oxide battery per kilogram battery, 6 versus 22 gCO_2e/kg. This difference is attributable to higher manufacturing energy requirements related to material processing assumed in Majeau-Bettez et al. Allocating impacts to only the first use of a technology removes the differences associated with battery lifetimes that extend beyond that of the vehicle. This assumption can have a significant effect on results considering the wide range of vehicle lifetimes assumed in the studies we reviewed. Assuming shorter vehicle lifetimes and battery requirements rounded to the nearest whole number tend to drive up estimated battery production impacts.

Studies of material availability for battery production indicate that lithium are likely sufficient for even relatively high penetration rates of Li-ion EVs (Gaines and Nelson 2010; Rydh and Svard 2003). Concerns about the rare earth elements used in NiMH batteries relate more heavily to the dominance of Chinese production capacity, 97 % of mine production in 2008, than global resource reserves (USGS 2009). Further discussion is provided in the SI.

Another aspect not yet well accounted for in the literature that is worth mentioning is differences between the battery management systems, electronic controls, and temperature control systems required for different battery technologies. This is primarily due to the rapidly evolving EV industry. Moving forward, improved data based on first generation EVs will help in better understanding the real lifetimes of EV batteries in use. As EV manufacturing matures together with related industries, studies will be better able to model the realities regarding battery down-cycling, reuse, and recycling.

3.2.3 Energy efficiency in the use phase of electric vehicles

Determining the specific energy use of electrical vehicles is complicated by a number of factors which introduce variability. For an ICEV, generally city driving results in greater energy use than highway driving. For an EV or HEV city driving can result in lower energy use than highway driving (US DOE 2010) due to the use of regenerative braking systems and smoothing of the engine revolution rate. Energy use is also dependent on charge–discharge efficiency, temperature control requirements, and the contribution of batteries to vehicle mass which is affected by AER and battery energy density.

In their study of battery technologies Van den Bossche et al. (2006) provide an overview of the properties of different battery types that are potentially cost-effective in the near-term and find Li-ion and NaNiCl or zebra battery technologies, achieve the highest energy densities, 60–150 and 125 Wh/kg, respectively; see Electronic Supplementary Material, Table S6. Burke et al. (Burke 2007) reports significant property differences in batteries designed for GI-HEVs and BEVs: for GI-HEVs 26 Wh/kg for the PbA battery tested, 45 to 47 for NiMH, and 56 and 77 for Li-Ion; for BEVs 34 Wh/kg for PbA, 68 for NiMH, and 105 and 140 for Li-ion. There is a tradeoff between power and energy in the design of a battery which can be well-described by a Ragone chart such as that provided by Van den Bossche et al. (2006). This tradeoff is significant when considering differences in the power requirements for fully electric versus hybrid vehicles. The range of energy density for Li-ion batteries is large with the lowest values coinciding with the energy density of NiMH, 60–70 Wh/kg. The power densities are highly variable with the high often more than twice the low value, and in the case of Li-ion, 80–2,000 W/kg, and NiMH, 200–1,500 W/kg, the ranges span an order of magnitude.

Shiau et al. (2008) analyzed the effect of mass on PHEVs and found electricity use in charge depleting mode increased by roughly 20 %, from 0.11 to 0.13 kWh/km when vehicle mass was increased by 60 %, from 1,520 to 2,410 kilograms.

The energy efficiency of storage is highest for Li-ion batteries at 90 % and lowest for NiMH at 70 % with NaNiCl falling between at 85 %. These values represent the energy output per energy input to the battery accounting for charge–discharge efficiency and the additional energy required to heat NaNiCl batteries (Van den Bossche et al. 2006). Losses during charging and discharging are related to the rate of charging and use phase power demand. In addition, losses occur naturally over time and certain battery configurations require additional energy use for temperature control. Shiau et al. (2008) estimate average fleet charge–discharge losses of 12 %.

Ambient temperature has been demonstrated to have a non-negligible effect on battery performance. For the Toyota Prius II, Yaegashi (Yaegashi 2005) reports reduced capacity of the NiMH battery in colder weather leading to reduced fuel economy. Fontaras reports a difference of 5-10 % in the fuel use of the Prius II between autumn/winter (avg. temps. 15°C/11°C) and spring/summer (avg. temps. 23°C/27°C) in Greece (Fontaras et al. 2008).

Differences in the energy use of vehicles themselves makes comparing between studies of different vehicle technologies a difficult task. Figure S1 in the Electronic Supplementary Material presents the energy use per kilometer collected from 6 studies. Values range from 0.1 to 0.2 kWh/km (0.4 to 0.8 MJ/km). Lower values around 0.1 kWh/km (0.4 MJ/km) are reported by studies of PHEVs in charge depleting mode with an AER of 30–100 km (Elgowainy et al. 2009; Shiau et al. 2008; Shiau et al. 2010). Shiau et al. (Shiau et al. 2010) simulate the performance of PHEV designs and report a value of 0.123 kWh/km (0.44 MJ/km) for PHEVs with AER of 140 km and 0.117 kWh/km (0.42 MJ/km) for PHEVs with AERs of 30–60 km. Higher results are reported for earlier model vehicles

and vehicles with longer ranges are expected as battery mass scales with range and increases the energy use of operation, however, clearly other factors influence the overall value. Kalhammer et al. (2007) report 0.14 kWh/km (0.5 MJ/km) for the Tesla Roadster's with reported range of 400 km and 0.17 kWh/km (0.6 MJ/km) for the AC Propulsion eBox which is an EV based on the Toyota Scion with a range of 240 km. Higher electricity use, 0.22 kWh/km (0.8 MJ/km), was calculated by Graham (2001) by scaling values for the GM EV1 to their PHEV system with 100 km AER and was also reported by Parks et al. (Parks et al. 2007) for a PHEV with 30 km AER under charge-depleting operation. Huo et al. (2010) assume 0.24 kWh/km (0.86 MJ/km) for their study of the effect of EVs in China.

Although maintenance appears to be a smaller contribution to vehicle life cycle GWP, there are some interesting differences between ICEVs and EVs. Due to the increased complexity of hybrid drivetrains we might expect larger environmental impacts associated with maintenance. Nemry et al. (2008) find the GWP of spare parts production over the lifetime of GI-HEVs is 150–160 % that of an ICEV. McCleese and LaPuma (2002) consider 3 EV options and find energy consumption in the maintenance phase of EVs with Pb-acid, NiCd, or NiMH batteries is 4–5, ~2, and slightly less than that of an ICEV respectively. However increasing complexity and integration of electronic components is a general trend across vehicle types (Syversen and Sandberg 2009), indicating that perhaps this difference will not be so pronounced. Moving forward, there is need for good studies addressing the performance of EVs under real-world driving conditions addressing maintenance-related impacts together with the effect of consumer behavior and driving patterns.

3.2.4 Electricity generation, transmission, and distribution

To compare electric vehicles with other vehicle options we must understand the comparison between the energy use and emissions associated with electricity and those associated with other fuel options. For most impact categories, the use phase is the dominant contributor to the overall life cycle impact of ICEVs. The use phase is also dominant for EVs in areas with a fossil-dominant electricity mix, however for certain low-impact electricity mixes the contribution of the use phase may be significantly reduced. Here we extract values from two data sources commonly used in life cycle studies of transportation, the EcoInvent database (Swiss Center for LCI 2009) and the GREET model (Furuholt 1995). The structure and scope of these two sources differ. EcoInvent data are presented as unit processes in a more structured database format where supply chains, such as those associated with the production of infrastructure, can be tracked more directly while GREET considers primarily inputs to operation and selected other supply chains, for example rolled up energy use and emissions associated with production of electricity generation infrastructure. Regardless, the contribution of infrastructure is small and the GWP values obtained from the two sources are in close agreement. The two data sources are complimentary. GREET provides more options for advanced fossil-based technologies such as an coal integrated gasification combined-cycle (IGCC), natural gas combined-cycle (NGCC) technologies, and biomass-based options. EcoInvent provides better representation of solar PV, wind, and hydro options because of its explicit treatment of infrastructure.

GWP estimates for electricity generation found in EcoInvent and GREET range from 550 gCO_2e/MJ for industrial gas to near zero values for direct-fired and IGCC biomass options. The GWP of EV operation can be approximated using an assumed energy efficiency, here we use 0.53 MJ/km based on an EPRI target (Axsen et al. 2008). Values for electricity generated from hard coal are generally in the range 350–380 gCO_2e/MJ (160–190 gCO_2e/km), however with EcoInvent country-specific estimates range from 300 gCO_2e/MJ for Portugal, Austria, and the Nordic mix to 430 gCO_2e/MJ for China. Coal IGCC results in slightly lower emissions of 280 gCO_2e/MJ. Similarly, averages for conventional natural gas generation range from 200 to 210 gCO_2e/MJ (100–110 gCO_2e/km) with country-specific variation 150 gCO_2e/MJ for Great Britain and France to 300 gCO_2e/MJ for Luxembourg. NGCC has the lowest emissions of fossil-based options, 150 gCO_2e/MJ (80 gCO_2e/km). Non-fossil options such as large (>600 kW) wind turbines, 5 gCO_2e/MJ, nuclear, 3–5 gCO_2e/MJ, or hydropower, 1–8 gCO_2e/MJ, have significantly lower emissions. For fossil-based electricity generation, although fuel combustion dominates the overall LCI, however feedstock production is not insignificant, contributing 5 to 10 %. It should also be noted that electricity mixes vary regionally, seasonally, by time of day, and will potentially be affected by EV market penetration or other future changes to the electricity market. Gaining a better understanding of charging habits, EV-related demand, and the effect of these factors on impacts could improve the precision of EV use phase impact estimates (Weber et al. 2010; Nansai et al. 2002). In section 3.2.6 we place these values in context by combining them with literature values for other life cycle phases.

3.2.5 End of life

Most studies of the environmental impacts of EVs do not consider impacts associated with the disposal, reuse, or recycling of vehicle components. In other cases authors state that the end-of-life phase is not significant with respect to GWP in particular life cycle (Samaras and Meisterling 2008). However, when assumptions are made about the

allocation of impacts of reused or recycled components, these assumptions could potentially be significant relative to the impacts of vehicle production. For example, for total impacts characterized using the hierarchical Eco-Indicator 99 method, Spielman and Althaus (2007) findthe full life cycle impacts of an ICEV would be reduced by 11 % and Van den Bossche et al. (2006) find recycling can offset roughly half of the impacts of battery production. Neither study specifies the contribution of GHG to the overall result. As the hierarchical Eco-Indicator 99 method places a relatively high emphasis on resource use, the impact of recycling on GHG impacts is potentially less significant. Dewulf et al (2010) perform an exergy comparison of a Li-ion battery supply chain based on primary materials and another based on recycled materials and find batteries based on recycled materials reduce the total exergy, fossil energy demand, and nuclear energy demand of the system all by roughly half. Often more qualitative claims are made about how the impacts of batteries in EVs should be reduced as a portion of the impact can be allocated to post-vehicular use as stationary power backup systems. However, a better understanding of the value and of the storage capabilities of post-vehicular batteries for backup power is needed before impacts can be allocated to this downstream use.

3.2.6 Comparison to conventional vehicles

Figure 5 provides a summary of results comparing current understanding of BEVs with ICEVs. The impact of vehicle production is estimated to be 35 gCO_2e/km for all vehicles with the exception of two cases, the Mercedes S and VW Golf A4, where we took the manufacturer's results to provide a benchmark (Volkswagon 2008; Mercedes-Benz 2008; Finkbeiner et al. 2006; Schweimer and Levin 2000). An additional impact of 12 gCO_2e/km associated with battery production is added for BEVs. In all cases except the Mercedes S and VW Golf A4 the supply chain GWP of U.S. diesel, 9.2 gCO_2e/MJ, and conventional unleaded gasoline, 12 gCO_2e/MJ, are used (ANL 2009) together with fuel use of 1.2 MJ/km for the Honda Insight HEV and Smart fortwo ICEV, 2.7 MJ/km for the generic diesel ICEV and 3.3 MJ/km for the generic gasoline ICEV. EV energy use is assumed to be equal to the Electric Power Research Institute PHEV target of 0.53 MJ/km (Axsen et al. 2008). This comparison is not intended to provide a definitive ranking of the Mercedes S and VW Golf A4 with respect to other technologies, rather these two are representative of presumably high quality LCA studies performed with the benefit of manufacturers' detailed, supply chain-specific data. It is likely the higher impacts associated with the Mercedes study in particular stem from the inclusion of considerations omitted from the simpler models and its larger size and mass.

The highest impacts, 315, 313, and 271 gCO_2e/km are obtained for the larger ICEVs, the Mercedes S and the generic gasoline and diesel vehicles modeled by GREET 1.8c. Impacts for the smaller VW Golf A4, 177 gCO_2e/km, Smart fortwo diesel, 128 gCO_2e/km, and Honda Insight gasoline-driven GI-HEV, 125 gCO_2e/km, fall between those of the BEV possibilities. The general trend is that BEVs or PHEVs in charge depleting mode using low GWP electricity perform best; followed by HEVs, PHEVs operating in charge sustaining mode, and highly efficient ICEVs;

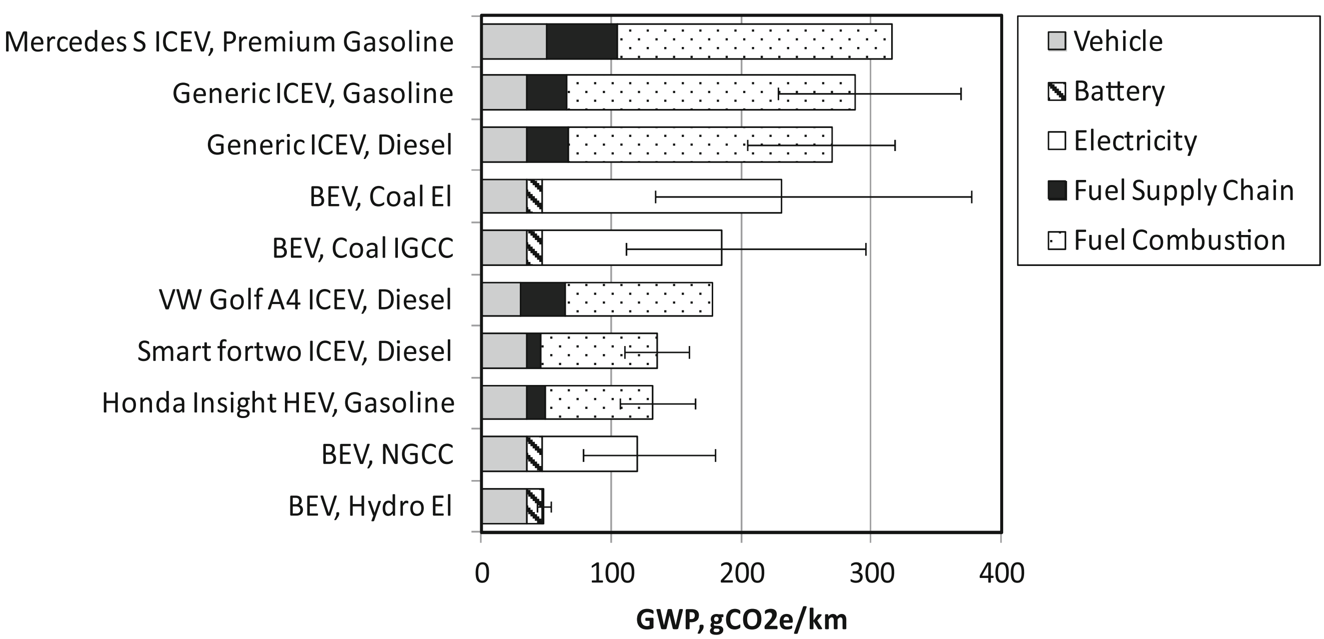

Fig. 5 Comparison of life cycle global warming potential per kilometer driven

followed by BEVs and PHEVs in charge depleting mode using conventional coal electricity; and finally followed by conventional ICEVs. This trend should be taken as *suggestive* of expected outcomes. Uncertainty and variability represented by the error bars as well as differences in the studies compared do not allow for a definitive conclusion.

In the use phase of BEVs we include results for 4 electricity generation technologies. Coal electricity, 350 gCO_2e/MJ, provides the high extreme for BEVs at 231 gCO_2e/km. Hydroelectricity, 1.7 gCO_2e/MJ (0.9 gCO_2e/km) provides the low extreme, 48 gCO_2e/km. We find a BEV powered by coal IGCC electricity, 260 gCO_2e/MJ has almost the same GWP as the VW Golf A4 diesel, 185 versus 177 gCO_2e/km, respectively, but higher life cycle GWP than the Smart fortwo or the Honda Insight, 135 and 132 gCO_2e/km, respectively. A BEV powered by NGCC electricity, 140 gCO_2e/MJ performed better than any of the ICEV options, 120 gCO_2/km.

Error bars on ICEV results represent possible variation of the impact of the fuel supply chain and the rate of fuel consumption. For fuel supply chain the Norwegian case provides the low, 3.3 and 6.0 gCO_2e/MJ for diesel and gasoline, and the European average low-S diesel and gasoline, 12 and 17 gCO_2e/MJ provide the high. For fuel consumption high and low are estimated as ±20 % of reported values. Error bars on EV results represent variation in electricity consumption, 0.2–0.8 MJ/km and a possible deviation of the impact of battery production, 5–15 gCO_2e/km or ±50 %.

We find these sources of uncertainty and/or variability in results are significant in determining the relative benefits of EVs and could potentially result in shifts in the ranking of GWP results. Results for EVs are more uncertain than those for ICEVs owing primarily to variability in use phase energy use estimates. While there is still non-negligible uncertainty around the impacts of battery production, primarily surrounding battery lifetimes and replacement schedules, it would appear improving our understanding of EV energy use and the charging grid mix is the most important next step for providing useful comparisons between EVs and ICEVs. Uncertainty in GWP of battery production is secondary, but can become significant to the EV-specific result when the use phase impacts are very low. When considering coal electricity, ±5 gCO_2e/km associated with battery production is swamped by the uncertainty related to rate of energy use while in the case of hydroelectricity it reflects a 10 % change in the life cycle GWP. The scale of these uncertainties reflects the need for improved LCA of EVs in order to better inform transportation policy-making.

3.3 Other emissions

Results related to impact categories other than global warming were less often reported in the literature. Figure S8 in the Electronic Supplementary Material summarizes results from selected studies. Within studies including other emissions, there are a number of differences which complicate direct comparisons, some presented results for electrification of different vehicle classes, such as Duvall (Duvall 2005) who presents results for compact cars, mid-size SUVs, and full-size SUVs, Parks et al. (Parks et al. 2007) present the current and anticipated future situations, Burnham et al. (Burnham et al. 2006) present results for reformulated gasoline (RFG) vehicles, and McClease and LaPuma (McCleese and LaPuma 2002) present results for BEVs utilizing different battery technologies (PbA, NiCd, NiMH). Variability in results reflects differences in electricity mix and technology assumptions. Results are biased by differences in system boundary. Only Wang et al. (1997), Burnham et al. (2006), and McClease and LaPuma (2002) include vehicle production. Burnham et al. (2006) and McCleese and LaPuma (2002) include PbA and NiMH but not Li-ion batteries. We collected results for emissions of VOCs, CH_4, SO_x, N_2O, PM_{10}, CO, HC, and NO_x per kilometer. Not all studies provided all results. The results of McCleese and LaPuma (2002) are higher than those of the other studies for VOC, PM_{10}, CO, HC, and NO_x. Estimates of CO, NO_x, and SO_x emissions are significantly higher from studies including vehicle production. In the case of VOC, CH_4, N_2O, and PM_{10}, we might assume vehicle production emissions are relevant as only these studies quantify these emissions. Because of the strong variability between the studies and the fact that only McCleese and LaPuma quantify other emissions for BEVs, it is not possible to draw conclusions regarding comparisons between BEVs and other vehicle types. Burnham et al. (2006) consider both ICEVs, GI-HEVs, and PHEVs within in a single model and provide full life cycle results for a number of emissions. They find slightly lower emissions of VOC, CH_4, and N_2O; only small differences for PM_{10}, CO, and NO_x; and slightly higher emissions of SO_x associated with GI-HEVs and PHEVs.

King and Webber (2008) performed the only study identified in our search addressing water use associated with adoption of electricity and find that water withdrawals are 40 times higher and water consumption double for EVs when compared with ICEVs. For their scenario, they report water withdrawals associated with electricity production of 80 L/kWh or 40 L/km driven. King and Weber also report water consumption, defined as water extracted and not returned to the same source, of 2 L/kWh or 0.75 L/km. For gasoline ICEVs they estimate withdrawals of 50 L/gallon gasoline or 1.5 L/km and consumption of 5–10 L/gallon gasoline or 0.2–0.3 L/km and.

3.4 Other impacts associated with batteries

If EVs are implemented to reduce GHG emissions the EV batteries are a source of environmental impact which must

be explicitly considered. GHG and possibly more importantly toxic emissions are connected to the processing of materials and manufacture of the batteries (Rydh 2003). The choice of how the materials contained in batteries are handled at the end of the battery's useful life, recycling, downcycling, or disposal is an important factor in determining environmental impact. In their study, Van den Bossche et al. (2006) find the avoided impacts associated with recycling and re-use of materials can result in a 50 % reduction of all battery-related impacts using hierarchical Eco-indicator 99 as the measure (Van den Bossche et al. 2006). From a cost perspective the case for battery recycling remains to be made. Material quality issues are a formidable challenge for recycling of lithium and rare earth metals. For these reasons, the rhetoric around end of life batteries often refers to down-cycling, re-using batteries in other applications such as stationary energy storage. Chitwood of Toyota Motors however expressed the view that plans for down-cycling Li-ion batteries often over-estimate their useful lifetime (Chitwood 2009).

Due to low energy density of current battery technologies, BEVs and PHEVs require a relatively large battery mass to achieve a relatively short AER. This fact stresses the need for the continued development of highly energy dense batteries if EVs are to be adopted on a societal scale. BEVs, PHEVs, and GI-HEVs differ in their power and energy requirements.

3.5 Other differences between electric and internal combustion engine vehicles

When we set out to perform this study we expected to find at least some studies of the production of additional electronic control systems, more complex hybrid transmission systems, or changes to the structural design and additional structural support associated with battery mass and describing implications for the comparative environmental impacts of EVs and ICEVs. What we found was that there is a clear gap in the literature in these areas. In terms of drivetrain design, GI-HEVs and PHEVs are much more complex than ICEVs. This complexity comes with more electronic control systems. The high impact of electronic components in general has been demonstrated in earlier LCA studies (Williams et al. 2002; Williams 2004). The production of electric equipment requires many different materials which poses a challenge for recycling and raises concerns about toxicity (Johnson et al. 2007). Beneficiation of precious metals and the production of high-grade silicon are energy and GHG intensive (Choi et al. 2006; Williams 2004; Kuehr and Williams 2003; Taiariol et al. 2001).

Furthermore, GREET 2.7 estimates 40 % of the total GWP of conventional vehicle production is associated with the drivetrain and transmission. The impacts of HEVs should be higher than those of conventional vehicles as they include additional drivetrain and transmission systems. In addition to this, through conversations with vehicle manufacturers, we have confirmed for longer AER battery mass must be considered in the structural design of vehicles (Meland 2009; Ruhland 2009; Shiau et al. 2009).

3.6 Advanced grid interaction and battery swapping

The time required to charge a battery depends primarily on battery chemistry, battery capacity, and the charging voltage. Using a 240 V system, a 15 kWh PHEV Li-ion battery can be charged in 3.6 hours (Duvall 2005). If widely adopted, the charging of EV batteries could have an effect on the environmental profile of electricity. Although simultaneously charging a large EV fleet has the potential to increase peak electricity demand and create impacts associated with investments in new generation, transmission, distribution capacity, and potentially increases associated with the marginal power source (Hacker et al. 2009); however, others have found that for expected penetration rates and charging patterns, EVs would likely not result in increases to peak demand (Lemoine et al. 2008; Ford 1994; Nansai et al. 2002). However, both Elgowainy et al. (Elgowainy et al. 2009) and Samaras and Meisterling (2008) provide detailed analyses of the impacts of electricity use by PHEVs and find increases in AER of the PHEVs resulted in lower system-wide GHG emissions except when the electric grid mix was dominated by coal or oil generation. Managed charging offers a means of minimizing the need for additional capacity through timing charging to avoid peak periods. In the near-term, a simple form of managed charging is the advanced grid interaction option most likely to be implemented. Lemoine et al. provide an argument showing modest tariffs could be used effectively to promote off-peak charging of PHEVs in California (Lemoine et al. 2008).

Vehicle-to-grid systems refer to schemes whereby vehicles could return power to the grid. Gage (2003) demonstrated the feasibility of energy storage and distributed generation using EVs. Although vehicle-to-grid systems could reduce peak generation demand, there are many reasons why this will not or should not be implemented until major technological barriers are overcome. Returning electricity from batteries to the grid increases the frequency of charge–discharge cycles and reduces the lifetime of batteries. While batteries show potential for transportation energy storage, they should be compared to alternatives such as pumped hydro to evaluate their benefits for stationary energy storage. Batteries are a relatively inefficient way to store electricity, high losses, high battery cost, low capacity per battery, and the small number of EVs expected all discourage a vehicle-to-grid connection. Gage (2003) also

demonstrates a system where the ICE of an HEV is used as a generator. The potential of such a system for generating power in special circumstances or in an emergency are positive; however, the impacts of trading other generation options for one based on transport fuel in terms of resource use, GHG mitigation, and human health impacts almost certainly exceed the impacts of the existing generation system.

Battery exchange systems such as the one promoted by Better Place have received considerable attention and venture capital recently (Better Place 2009). However, success of a battery exchange system requires standardization of battery technologies and vehicle connections as well as vehicles with removable batteries. In the near-term, battery exchange systems are unlikely to succeed due to the large size and weight of EV batteries, vehicle designs which do not allow easy battery removal, and safety concerns and system integrity concerns on the part of vehicle manufacturers (Chitwood 2009; Meland 2009). In addition, battery exchange programs could multiply the impact of EVs by increasing the required number of batteries and reducing battery lifetime due to increased stress on the battery packs.

4 Conclusions

Based on our survey of 51 environmental assessments of hybrid and electric vehicles, we find no single study contains a complete assessment of electric vehicles. In general, more studies include the LCI of fuels and electricity than the LCI of the vehicle itself. Details pertaining to key vehicle components such as the battery or drivetrain are even less documented. GWP is the most frequently reported result followed by acidification (SO_2, NO_x), smog (CH_4, NMVOC, NO_x), and toxicity impacts. Considering the complexity of the vehicle supply chain, there are few well-populated and transparent LCI datasets for EVs, a situation which is likely to cause significant error associated with omission or insufficient representation of production processes.

In the terms of total life cycle, the GHG impacts of EVs are heavily dependent on use phase energy consumption and the electricity mix used for charging. BEVs powered by coal fired electricity appear to perform better than conventional ICEVs in terms of GWP. High-efficiency vehicles such as the Smart fortwo ICEV or Honda Insight GI-HEV appear to have lower associated GWP than BEVs with coal electricity. However EVs powered by lower-carbon electricity such as hydro- or NGCC offer GWP reductions over these efficient ICEVs and GI-HEVs. While it appears based on our findings that EVs perform better than conventional ICEVs, it is possible we are not comparing apples to apples as the typical size of an EV is likely smaller than an ICEV. Caution is warranted in drawing conclusions based on small differences considering uncertainties and variability across studies.

In terms of production, there are still a number of gaps to be filled in our understanding of the differences in the impacts of EV and ICEV production. Differences relating to vehicle production are relatively minor within the context of the life cycles of ICEVs or BEVs using fossil-based electricity as the use phase is responsible for 60–90 % of life cycle GWP. Nonetheless, differences in production-related impacts are relevant for certain decisions such as choosing between technologies which are potentially cost-effective in the near-term. It is also important to understand the effect of production-related differences on impacts other than GWP to avoid problem-shifting. Batteries are the most studied component of EVs, but only a small number of transparent battery LCIs are publicly available. Many studies reviewed are based on very crude LCIs of battery production. As modern EV designs are evolving rapidly, the detail and quality of stylized studies estimating their impacts may be more uncertain or less complete than industry-sponsored studies such as those that have been done of ICEVs and are just beginning to surface for EVs.

Differences between studies and the lack of access to detailed inventories make comparison of impacts other than GWP across studies very uncertain. Trends suggested by the existing data indicate lower emissions of VOC, CH_4, and N_2O associated with the life cycle of EVs when compared with ICEVs. Similarly PHEVs and BEVs demonstrate and slightly higher life cycle emissions of SO_x when compared with the life cycle of ICEVs, a difference that is likely associated with the use of coal-fired electricity. Brinkman et al. (2005)suggest electricity use in vehicles would also have higher associated PM_{10} due to coal combustion; however, our review did not provide enough data points for comparison. Our review did not reveal significant differences for PM_{10}, CO, and NO_x.

Based on the results of our survey, the most important next steps toward understanding the impacts of EVs relative to ICEVs are improving our estimates of the impacts associated with the electricity used to charge a growing EV fleet; obtaining well-informed and comparable estimates of use phase energy consumption for different vehicle options and driving patterns; improving our understanding of vehicle lifetime and battery replacement schedules; developing transparent, rigorous, and publicly available LCIs of EV production; and quantifying the effects of vehicle end of life scenarios. LCIs of EV production should focus on batteries, control electronics, electric motors and their magnets, EV transmissions, and on-board chargers. With respect to batteries, it is also important to improve our understanding of the fate of material contained in EV batteries. Toxic metal emissions should be tracked and their impacts

characterized. Better information related to the use phase driving patterns of EV users and characterizing the impacts of regional and time-related electricity mixes could help identify subsets of drivers for which EVs could yield significant environmental benefits.

Overall, gaps in existing environmental assessments of EVs are significant. Given current understanding of a transportation system including significant use of EVs it appears that in connection with low-carbon electricity systems, BEVs and PHEVs offer the potential of reductions in GHG emissions when compared with conventional ICEVs, however their relative position in terms of GHG emissions when compared to other advanced vehicle technologies such as high-efficiency ICEVs or GI-HEVs is less clear.

Acknowledgments This research was made possible by the Norwegian Research Council under the E-Car Project, grant #190940. The opinions are those of the authors. We thank Edgar Hertwich and Francesco Cherubini for their critical reviews of earlier drafts of this work and three anonymous reviewers for their comments which contributed to significant improvements in our manuscript.

References

Andersson B, Råde I (2001) Metal resource constraints for electric-vehicle batteries. Transport Res Part D 6:297–324

ANL (2009) Greenhouse gases, regulated emissions, and energy use in transportation (GREET) Model v. 1.8c. Argonne National Lab., Univ. of Chicago, Chicago, Illinois, USA

Axsen J, Burke A, Kurani K (2008) Batteries for plug-in hybrid vehicles (PHEVs): Goals and state of the technology circa 2008. Inst. of Transportation Studies, Univ. of California, Davis

Bandivadekar AP (2008) Evaluating the impact of advanced vehicle and fuel technologies in U.S. Light-Duty Vehicle Fleet. Massachusetts Institute of Technology

Baptista P, Silva C, Gonçalves G, Farias T (2009) Full life cycle assessment of market penetration of electricity based vehicles. Paper presented at the EVS24, Stavanger, Norway

Bauen A, Hart D (2000) Assessment of the environmental benefits of transport and stationary fuel cells. J Power Sources 86(1–2):482–494

Bellona (2009) Norges helhetlige klimaplan. Bellonameldingen (2008–2009)

Better Place (2009) Battery Exchange Stations. http://www.betterplace.com/our-bold-plan/how-it-works/battery-exchange-stations. Accessed April 29, 2009 2009

Boureima F, Messagie M, Matheys J, Wynen V, Sergeant N, Van Mierlo J, De Vos M, De Caevel B (2009) Comparative LCA of electric, hybrid, LPG and gasoline cars in Belgian context. Paper presented at the EVS24, Stavanger, May 13–16, 2009

Bravo J, Silva CM, Farias TL (2006) Simulation of hybrid electrical vehicles. Instituto Superior Técnico (Technical University of Lisbon), Lisbon, Portugal

Brinkman N, Wang M, Weber T, Darlington T (2005) Well-to-wheels analysis of advanced fuel/vehicle systems—a North American study of energy use, greenhouse gas emissions, and criteria pollution emissions. Argonne National Laboratory, U.S. Dept. of Energy, Chicago, Illinois

Buchert M (2010) Life cycle assessment (LCA) of nickel metal hydride batteries for hev application. In: Int. Automobile Recycling Congress, March 4, 2010, Basel, Switzerland

Burke A, Abeles E (2004) Feasable CAFE standard increases using emerging diesel and hybrid-electric technologies for light-duty vehicles in the United States. Inst. of Transportation Studies, Univ. of California, Davis

Burke AF (2007) Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles. Proc IEEE 95(4):806–820

Burnham A (2009) Researcher, Argonne National Laboratory. Argonne, IL. Personal communication

Burnham A, Wang M, Wu Y (2006) Development and applications of GREET 2.7—the transportation vehicle-cycle model. Argonne National Lab., Univ. of Chicago, Chicago, Illinois

Campanari S, Manzolini G, Garcia de la Iglesia F (2009) Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. J Power Sources 186 (2):464–477

Chitwood J (2009) Future fuels and environmental strategy manager, Toyota motor sales, North America. Torrence, California

Choi B-C, Shin H-S, Lee S-Y, Hur T (2006) Life cycle assessment of a personal computer and its effective recycling rate. Int J Life Cycle Assess 11(2):122–128

Commission on Oil Independence (2006) Making Sweden an OIL-FREE Society

Daniel JJ, Rosen MA (2002) Exergetic environmental assessment of life cycle emissions for various automobiles and fuels. Exergy 2 (4):283–294

Dewulf J, Van der Vorst G, Denturck K, Van Langenhove H, Ghyoot W, Tytgat J, Vandputte K (2010) Recycling rechargeable lithium ion batteries: critical analysis of natural resource savings. Res Cons Recycling 54(4):229–234

Dhingra R, Overly JG, Davis GA, Das S, Hadley S, Tonn B (2000) A life-cycle-based environmental evaluation: materials in new generation vehicles. SAE Tech. Paper Series. Oak Ridge National Lab., Univ. of Tennesee

DieselNet (2000) ECE 15 + EUDC/NEDC. http://www.dieselnet.com/standards/cycles/ece_eudc.html. Accessed July 3, 2009 2009

Duvall MS (2005) Battery evaluation for plug-in hybrid electric vehicles. In: Vehicle power and propulsion, 2005 IEEE Conference, pp 338–343

Eberhard M, Tarpenning M (2006) The 21st Century Electrical Car. Tesla Motors Inc

Elgowainy A, Burnham A, Wang M, Molburg J, Roussau A (2009) Well-to-wheel analyisi of energy use and greenhouse gas emissions analysis of plug-in hybrid electric vehicles. Argonne National Lab., Univ. of Chicago, U.S. Dept. of Energy, Chicago, Illinois

EPRI (2002) Comparing the benefits and impacts of hybrid electric vehicles options for compact sedan and sport utility vehicles. Electric Power Research Inst, Palo Alto

EPRI (2007) Environmental assessment of plug-in hybrid electric vehicles volume 1: nationwide greenhouse gas emissions. Electric Power Research Inst, Palo Alto

Finkbeiner M, Hoffmann R, Ruhland K, Liebhart D, Stark B (2006) Application of life cycle assessment for the environmental certificate of the Mercedes-Benz S-Class. Int J Life Cycle Assess 11 (4):240–246

Fontaras G, Pistikopoulos P, Samaras Z (2008) Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles. Atmos Environ 42(18):4023–4035

Ford A (1994) Electric vehicles and the electric utility company. Energy Policy 1994(22):7

Furuholt E (1995) Life cycle assessment of gasoline and diesel. Res Cons Recycling 14:251–263

Gage TB (2003) Development and Evaluation of a Plug-in HEV with vehicle-to-grid power flow. AC Propulsion, Inc

Gaines L, Burnham A, Rousseau D, Santini D (2007) Sorting through the many total-energy-cycle pathways possible with early plug-in

hybrids. Argonne National Lab., Univ. of Chicago, U.S. Dept. of Energy, Chicago, Illinois

Gaines L, Nelson P (2010) Lithium-ion batteries: examining material demand and recycling issues. In: Proceedings of the 2010 TMS Annual Meeting & Exhibition, Sustainable Materials Processing and Production Symposium, Seattle, Washington, 2010

General Motors Corporation (2001) Well-to-wheel energy use and greenhouse gas emissions of advanced fuel/vehicle systems—North American Analysis

Graham R (2001) Comparing the benefits and impacts of hybrid electric vehicle options. Electric Power Research Institute, Palo Alto

Greenpeace (2008) Energy revolution: a sustainable global energy output. Greenpeace, New York, New York

Hacker F, Harthan R, Matthes F, Zimmer W (2009) Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe. Oeko-Institut e.V. for the The European Topic Center on Air and Climate Change, under a European Environmental Agency Grant, Berlin, Germany

Hackney J, de Neufville R (2001) Life cycle model of alternative fuel vehicles: emissions, energy, and cost trade-offs. Transport Res A-Pol 35(3):243–266

Hawkins T, Hendrickson CT, Higgins C, Matthews HS (2007) A mixed-unit input–output model for environmental life-cycle assessment and material flow analysis. Environ Sci Technol 41 (3):1024–1031

Hermance D, Sasaki S (1998) Hybrid electric vehicles take to the streets. IEEE Spectr 35(11):48–52

Huo H, Zhang Q, Wang M, Streets D, He K (2010) Environmental implication of electric vehicles in China. Environ Sci Technol 44 (13):4856–4861

ISO (2006a) 14040 Environmental management—life cycle assessment—principles and framework. International Organization for Standardization, Geneva

ISO (2006b) 14044 Environmental management—life cycle assessment—requirements and guidelines. International Organization for Standardization, Geneva

Jacobson MZ (2009) Review of solutions to global warming, air pollution, and energy security. Energy Environ Sci 2(2):148–173

Jaramillo A, Samaras C, Wakeley H, Meisterling K (2009) Greenhouse gas implications of using coal for transportation: life cycle assessment of coal-to-liquids, plug-in hybrids, and hydrogen pathways. Energy Policy 37:2689–2695

Johnson J, Harper EM, Lifset R, Graedel TE (2007) Dining at the periodic table: metals concentrations as they relate to recycling. Environ Sci Technol 41(5):1759–1765

Joshi S (2000) Product environmental life-cycle assessment using input–output techniques. J Ind Ecol 3(2 & 3):95–120

Kalhammer FR, Kopf BM, Swan DH, Roan VP, Walsh MP (2007) Status and prospects for zero emissions vehicle technology. Air Resource Board Independent Expert Panel 2007

Karbowski D, Haliburton C, Roussau A (2007) Impact of component size on plug-in hybrid vehicle energy consumption using global optimization. Transportation Technology R&D Center, Argonne National Lab., Univ. of Chicago, U.S. Dept. of Energy

Kazimi C (1997) Evaluating the environmental impact of alternative-fuel vehicles. J Environ Econ Manage 33(2):163–185

Kendall G (2008) Plugged in the end of the oil age. WWF

King C, Webber M (2008) The water intensity of the plugged-in automotive economy. Environ Sci Technol 42(12):4305–4311

Kitner-Meyer M, Schneider K, Pratt R (2007) Impacts assessment on plug-in hybrid vehicles on electric utilities and regional U.S. power grids part 1: technological analysis. Pacific Northwest National Lab., U.S. Dept. of Energy, Richland, Washington

Kuehr RD, Williams E (2003) Computers and the environment: understanding and managing their impacts. Eco-efficiency in industry and science, vol v. 14. Kluwer Academic, Dordrecht

Lave L, Hendrickson CT, McMichael FC (1995a) Environmental implications of electric cars. Science 268:993–995

Lave L, Wecker W, Reis W, Ross D (1990) Controlling emissions from motor vehicles: a benefit–cost analysis of vehicle emission control alternatives. Environ Sci Technol 24(8):1128–1135

Lave LB, Cobas-Flores E, Hendrickson C, McMichael FC (1995b) Using input–output analysis to estimate economy-wide discharges. Environ Sci Technol 29(9):420A–426A

Lave LB, MacLean HL (2002) An environmental–economic evaluation of hybrid electric vehicles: Toyota's Prius vs. its conventional internal combustion engine Corolla. Transport Res D-TR E 7(2):155–162

Lemoine D, Kammen D, Farrell A (2008) An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles. Environ Res Letters 3:1–10

Letendre S, Watts R, Cross M (2008) Plug-in hybrid vehicles and the vermont grid: a scoping analysis. Univ. of Vermont, Burlington, Vermont

Majeau-Bettez G, Hawkins T, Strømman A (2011) Life cycle environmental assessment of first generation lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environ Sci Technol 45(10):4548–4554

Matheys J, Van Autenboer W, Timmermans J, Van Mierlo J, Van den Bossche P, Maggetto G (2007) Influence of functional unit on the life cycle assessment of traction batteries. Int J Life Cycle Assess 12(3):191–196

McCleese DL, LaPuma PT (2002) Using Monte Carlo simulation in life cycle assessment for electric and internal combustion vehicles. Int J Life Cycle Assess 7(4):230–236

Meland H (2009) Marketing Manager, Miljøbil Grenland AS. Porsgrunn, Norway

Mercedes-Benz (2008) Environmental Certificate, Mercedes-Benz S-Class. Daimler-Chrysler Communications, Stuttgart, Germany

Mercedes-Benz (2009) Environmental Certificate for the S 400 Hybrid. Daimler AG, Stuttgart, Germany

Mohamadabadi HST, Tichkowsky G, Kumar A (2009) Development of a multi-criteria assessment model for ranking of renewable and non-renewable transportation fuel vehicles. Energy 34(1):112–125

Nansai K, Tohno S, Kono M, Kasahara M (2002) Effects of electric vehicles (EV) on environmental loads with consideration of regional differences of electric power generation and charging characteristic of EV users in Japan. Appl Energ 71(2):111–125

Nemry F, Leduc G, Mongelli I, Uihlein A (2008) Environmental impact of passenger cars. Joint Res. Centre, Inst. for Prospective Tech. Studies, Seville, Spain

Notter D, Gauch M, Widmer R, Wäger P, Stamp A, Zah R, Althaus H (2010) Contibution of li-ion batteries to environmental impact of electric vehicles. Environ Sci Technol 44(17):6550–6556

Parks K, Denholm P, Markel T (2007) Costs and emssions associated with plug-in hybrid electric vehicle charging in the Xcel Energy Colorado Service Territory. National Renewable Energy Lab., U.S. Dept. of Energy, Golden, Colorado

Plotkin S, Santini D, Vyas A, Anderson J, Wang M, Bharathan D, He J (2002) Hybrid electric vehicle technology assessment: Methodology, analytical issues, and interim results

Rantik M (1999) Life cycle assessment of five batteries for electric vehicles under different charging regimes. KFB-Meddelande, vol 28. Chalmers Univ. of Technology, Göteborg, Sweden

Ruhland K (2009) Manager, certification, environment, and regulatory affairs, Mercedes-Benz Cars Development, Daimler AG. Sindelfingen, Germany

Rydh CJ (1999) Environmental assessment of NiCd-Battery manufacturing—past and present trends. In: ECO-Tech '99 2nd seminar on Ecological Technology and Management, Kalmar, Sweden, 22–24 September 1999. p 10

Rydh CJ (2001) Environmental assessment of battery systems in life cycle management. Chalmers Univ. of Technology, Göteborg, Sweden

Rydh CJ (2003) Environmental assessment of battery systems: critical issues for established and emerging technologies. Chalmers Univ. of Technology, Göteborg, Sweden

Rydh CJ, Karlstrom M (2002) Life cycle inventory of recycling portable nickel-cadmium batteries. Res Cons Recycling 34(4):289–309

Rydh CJ, Sanden BA (2005) Energy analysis of batteries in photovoltaic systems. Part I: performance and energy requirements. Energ Convers Manage 46(11–12):1957–1979

Rydh CJ, Svard B (2003) Impact on global metal flows arising from the use of portable rechargeable batteries. Sci Total Environ 302 (1–3):167–184

Samaras C, Meisterling K (2008) Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy. Environ Sci Technol 42(9):3170–3176

Santini D, Vyas A (2008) How to use life cycle analysis comparisons of PHEVs to competing powertrains. Argonne National Lab., Univ. of Chicago, U.S. Dept. of Energy, Chicago, Illinois

Schexnayder SM, Das S, Dhingra R, Overly JG, Tonn BE, Peretz JH, Waidely G, Davis GA (2001) Environmental evaluation of new generation vehicles and vehicle components. Engineering Science and Technology Division, Oak Ridge National Lab., U.S. Dept. of Energy, Oak Ridge, Tennessee

Schweimer GW, Levin M (2000) Life cycle inventory for the Golf A4. Environment and Transport, Volkswagen AG

Shiau C, Kaushal N, Hendrickson CT, Petersen SB, Whitacre JF, Michalek JJ (2010) Optimal plug-in hybrid electric vehicle design and allocation for minimum life cycle cost, petroleum consumption, and greenhouse gas Emissions. J Mechanical Design 132 (091013):1–6

Shiau C, Samaras C, Hauffe R, Michalek J (2009) Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles. Energy Policy 37(7):2653–2663

Shiau CSN, Samaras C, Hauffe R, Michalek JJ (2008) Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles Carnegie Mellon University, Pittsburgh

Shukla A, Kumar TP (2008) Materials for next-generation lithium batteries. Curr Sci 93:314–331

Singh M, Cuenca R, Formento J, Gaines L, Marr B, Santini D, Wang M, Adelman S, Kline D, Mark J, Ohi J, Rau N, Freeman S, Humphreys K, Placet M (1998) Total energy cycle assessment of electric and conventional vehicles: an energy and environmental analysis. Argonne National Lab., National Renewable Energy Lab., and Pacific Northwest National Lab., U.S. Dept. of Energy, Springfield, Virginia

Sioshansi R, Denholm P (2009) Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services. Environ Sci Technol 43(4):1199–1204

Spielman M, Althaus H (2007) Can a prolonged use of a passenger car reduce environmental burdens? Life cycle analysis of Swiss passenger cars. J Clean Prod 15(11–12):1122–1134

Spinella A (2007) Dust-to-dust energy report. CNW Marketing Research, Bandon

Spongenber H (2008) EU states plug in to electric cars. http://euobserver.com/882/26594. Accessed June 17, 2009

Stephan CH, Sullivan J (2008) Environmental and energy implications of plug-in hybrid-electric vehicles. Environ Sci Technol 42 (4):1185–1190

Suh S et al (2004) System Boundary selection in life-cycle inventories using hybrid approaches. Environ Sci Technol 38(3):657–663

EcoInvent 2.1 (2009) Swiss center for life cycle inventories, Zurich, Switzerland. http://www.ecoinvent.org/

Syversen F, Sandberg K (2009) Bilens indre—materialbruk og miljøgifter (The car's interior—material use and environmental toxins). Mepex & Bellona, Oslo

Taiariol F, Fea P, Papuzza C, Casalino R, Galbiati E, Zappa S (2001) Life cycle assessment of an integrated circuit product. In: IEEE Int. Symposium on Electronics and the Environment, Denver, Colorado

Takahashi M, Ohtsuka H, Akuto K, Sakurai Y (2005) Confirmation of long-term cyclability and high thermal stability of $LiFePO_4$ in prismatic lithium-ion cells. J Electrochemical Society 152:A899

Tesla (2009) 2009 Tesla roadster performance specifications. Tesla Motors. http://www.teslamotors.com/performance/perf_-specs.php. Accessed May 26th 2009

Toyota (2009) 2010 Prius: harmony between man, nature, and machine. Toyota Motor Sales U.S.A., Inc. http://www.toyota.com/byt/pub/buildGeneralEbrochure.do?brochureType=general&modelYear=2010&lang=en&seriesCode-12&zip=. Accessed June 17 2009

Tukker A, Poliakov E, Heijungs R, Hawkins T, Neuwahl F, Rueda-Cantuche J, Giljum S, Moll S, Oosterhaven J, Boumeester M (2008) Towards a global multi-regional environmentally extended input–output database. Ecol Econ 68(7):1928–1937

US DOE (2010) Model Year 2010 Fuel Economy Guide. Office of Energy Efficiency and Renewable Energy, U.S. Dept. of Energy and U.S. Environmental Protection Agency, Washington, DC

US EPA (2011) Motor Vehicle Emissions Simulator—MOVES. Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Washington, DC

USGS (2009) Mineral Commodity Summaries 2009. Reston, Virginia

Van den Bossche P, Vergels F, Van Mierlo J, Matheys J, Autenboer W (2006) SUBAT: an assessment of sustainable battery technology. J Power Sources 162(2):913–919

Van Mierlo J, Timmermans JM, Maggetto G, Van den Bossche P, Meyer S, Hecq W, Govaerts L, Verlaak J (2004) Environmental rating of vehicles with different alternative fuels and drive trains: a comparison of two approaches. Transport Res D-TR E 9(5):387–399

Vimmerstedt L, Jungst R, Hammel C (1996) Impact of increased electric vehicle use on battery recycling infrastructure. U.S. Dept. of Energy. http://www.osti.gov/bridge/servlets/purl/414298-uM4Ycx/webviewable/414298.pdf. Accessed March 12, 2009

Vimmerstedt LJ, Ring S, Hammel CJ (1995) Current status of environmental, health, and safety issues of lithium ion electric vehicle batteries. National Renewable Energy Lab., U.S. Dept. of Energy, Golden, Colorado

Volkswagon (2008) The golf environmental commendation. Volkswagon Automotive Group, Wolfsburg, Germany

Wang MQ, Plotkin S, Santini DJ, He J, Gaines L, Patterson P (1997) Total energy-cycle energy and emissions impacts of hybrid electric vehicles. Argonne National Lab., Univ. of Chicago, U.S. Dept. of Energy, Chicago, Illinois

Wang Q, DeLuchi MA, Sperling D (1990) Emission impacts of electric vehicles. J Air Waste Manag Assoc 40(9):1275–1284

Wang Q, Santini D (1993) Magnitude and value of electric vehicle emissions reductions for six driving cycles in four U.S. cities with varying air quality problems. Argonne National Lab., Univ. of Chicago, U.S. Dept. of Energy, Chicago, Illinois

WBCSD (2004) Mobility 2030: meeting the challenges to sustainability. World Business Council on Sustainable Development, Geneva, Switzerland

Weber C, Jaramillo P, Marriott J, Samaras C (2010) Life cycle assessment and grid electricity: what do we know and what can we know? Environ Sci Technol 44(6):1895–1901

Will FG (1996) Impact of lithium abundance and cost on electric vehicle battery application. J Power Sources 63:23–26

Williams E (2004) Energy intensity of computer manufacturing: hybrid analysis combining process and economic input–output methods. Environ Sci Technol 38(22):6166–6174

Williams E, Ayres R, Heller M (2002) The 1.7 kilogram microchip: energy and material use in the production of semiconductor devices. Environ Sci Technol 36(24):5504–5510

Williamson SS, Emadi A (2005) Comparative assessment of hybrid electric and fuel cell vehicles based on comprehensive well-to-wheels efficiency analysis. IEEE T Veh Technol 54 (3):856–862

Yaegashi T (2005) Automotive power-train towards sustainable development (Does hybridisation enable ICE vehicles to compete in the future?) Accessed online: http://powerlab.mech.okayama-u.ac.jp/~esd/comodia2004/000_key.pdf. As cited by: Fontaras G, Pistikopoulos P, and Samaras Z. "Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles." Atmos Environ 42:4023–4035

Zackrisson M, Avellan L, Orlenius J (2010) Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles—critical issues. J Clean Prod 18(15):1519–1529